suppressed. However, the model's performance decays gracefully for reasonable deviations from the optimal conditions (see Fig. 10 of Perrone and Stone, 1994).

Recently, Orban et al. (1992) showed that the response of MST neurons to translational (radial) flow is altered by the presence of rotational flow unlike neurons designed to respond to heading completely independently of rotation (see alternate models below). As we had postulated (Perrone, 1987, 1992; Perrone & Stone, 1994), their data show that MST neurons do not ‘decompose’ the flow field into its translational and rotational components as do other models of human heading estimation (Longuet-Higgins & Pradzny, 1980; Rieger & Lawton, 1985; Heeger & Jepson, 1992; Hildreth, 1992) but rather are tuned to specific combinations of flow components, i.e. they act as templates. Furthermore, other subsequently discovered properties of MST neurons (e.g. spiral tuning and invariance as described in Graziano et al., 1994) are predicted by our model (Stone & Perrone, 1994; Perrone & Stone, submitted). More recently, Duffy & Wurtz (1995) have described center-of-motion (in the case of pure radial motion, this is equivalent to heading) tuning in MST neurons similar to that predicted by our model. The template model has therefore already provided insight to physiologists into the responses of MST neurons (see discussion of Duffy & Wurtz, 1995).

After their study of human self-motion estimation in response to combined translation and rotation, Warren and Hannon (1990) concluded that humans can determine their self-motion from optic flow alone. Furthermore, their data ruled out most of the promising models of heading perception at the time in favor of a family of models called "differential motion models". Differential motion models (Longuet-Higgins & Pradzny, 1980; Rieger & Lawton, 1985; Hildreth, 1992) capitalize on the fact that translation component is a function of depth, while the rotational component is not. Therefore, the difference between flow-field vectors at adjacent points at different depths yields information related to the translation only. These models however require the existence of adjacent points at different depths (local depth differences) in order to subtract out the rotational component. We have performed a series of experiments (Stone & Perrone, 1993) together with simulations of the most robust differential motion model (Rieger & Lawton, 1985) under the same stimulus conditions (see Progress below). The "split-plane" stimulus was designed to attack the Achilles heal of the differential motion models: it provides no adjacent points at different depths, i.e. no local differential motion. We found that humans can determine their heading relatively accurately in the split-plane condition. However, simulations of the Rieger-Lawton model, even using optimal parameters, showed large errors inconsistent with the human performance data while simulations of our model showed small errors similar to those found in the human psychophysical data (see Progress Fig. 6). Differential motion models therefore cannot be used to predict human heading judgments.

Heeger and Jepson (1992) proposed a mathematical procedure for determining heading from arbitrarily combined translational and rotational flow fields without the need for local differential motion. Their algorithm takes advantage of the mathematical fact that five vectors within the flow field from points at different depths actually provide all the information necessary for solving the heading problem exactly even in the presence of arbitrary rotation. This algorithm could therefore be used as the basis for creating heading detectors that are totally unresponsive to observer rotation. The problem with this approach as a model for human heading estimation is two-fold: 1) it finds the exact solution and therefore appears inconsistent with the psychophysical finding of small but consistent systematic errors (Stone & Perrone, 1993, 1997), and 2) it results in detectors that are inconsistent with the physiological finding that the responses of MST neurons to their preferred flow component are in fact degraded by the presence of unpreferred flow components (Orban et al., 1992). More recently, Lappe and Rauschecker

(1993) have modified the Heeger-Jepson model to deal only with rotations caused by gaze stabilization and have implemented it using a two-layered neural network, ostensibly modeling MT to MST. In particular, because its output neurons are only unresponsive to the limited rotations experienced during gaze stabilization, the Lappe-Rauscheker model does not incorrectly predict perfect performance as does the original Heeger-Jepson model and it is not ruled out by the Orban data (Orban et al., 1992). However, it is inconsistent with the recent finding of explicit 2D bell-shaped heading tuning of individual MST neurons (Duffy & Wurtz, 1995).

In summary, our template model is the only current model of human heading estimation that is consistent with existing psychophysical measurements of human visual heading estimation (Rieger & Toet, 1985; Cutting, 1986; Perrone & Stone, 1994; Stone & Perrone, 1993, 1997) as well as the known visual response properties of MST neurons (Duffy & Wurtz, 1995; Graziano et al., 1994). Although it is clear that signals related to eye movement play a role in human heading estimation (Royden et al. 1992, 1994; Banks et al., 1996), we and others have shown that such signals are not <u>required</u> for accurate self-motion estimation (Rieger & Toet, 1985; Cutting, 1986; van den Berg, 1992; van den Berg & Brenner, 1994ab; Warren et al., 1996; Perrone & Stone, 1997). The recent studies of the effect of eye movements on MST responses to optic flow (Duffy & Wurtz, 1994; Bradley et al., 1996; Britten, personal communication) have documented a complex set of interactions that await explanation. The template model will ultimately be extended to utilize non-visual inputs (both vestibular and oculomotor) and, once spaceflight data become available, it will be asked to account for any effects of microgravity, but these efforts will be the subject of future proposals as they require the availability of additional physiological and psychophysical data.

Human heading estimation

As explained above, one cannot simply use the FOE to determine one's heading because the FOE only coincides with heading on the rare occasion when the observer travels in a straight line with his/her eyes stationary in the head. Generally, the observer translates while either actively tracking a stationary point of interest or his/her eyes are reflexively stabilized and the eyes rotate producing rotational flow. The resultant retinal flow field during forward translation with gaze-stabilization will be the sum of the translational (radial outward flow) and rotational (unidirectional flow) components, but these two components are constrained because of gaze-stabilization (for a mathematical presentation see, Stone & Perrone, 1997). Note that eye rotation distorts the expansion pattern: the focus of expansion in the direction of heading is eliminated and a singularity (false FOE) is created in the direction of gaze (Fig. 1A). If the observer travels along a curved path (i.e. translates and rotates) while fixating an object along (or outside) their curved path that is moving with him/her (e.g. the car in front) or if the observer tracks an independently moving object while translating, then the optic flow will contain a combination of rotational and translational flow which is inconsistent with the gaze-stabilization hypothesis (Fig. 1B). The fact that in all the above cases, heading is shifted away from the FOE raised the important question of whether or not humans can distinguish where they are going (heading indicated by the open square) from where they are looking (gaze indicated by the cross) (Regan and Beverly, 1979). We and others have shown that, at least under some conditions, humans can do so (Rieger & Toet, 1985; Cutting, 1986; Stone & Perrone, 1997). **The major questions that we wish to address in the proposed study is whether accurate performance in visual heading estimation does not require that one's head be upright with respect to gravity (hypothesis 1), but does require that the optic flow be consistent with gaze stabilization (hypothesis 2) and be free of roll (hypothesis 3). We also wish to test whether theoretical constraints (Koenderink & van Doorn, 1987) and the response ranges of MT neurons (Maunsell & van Essen, 1983b; Mikami, et**

al., 1986; Rodman & Albright, 1987; Lagae et al., 1993) dictate the range of translation and rotation rates that can be accurately processed (hypothesis 4).

Gaze stabilization

Primates possess a number of eye-movement mechanisms that serve to stabilize gaze during self-motion. In addition to the classical rotational vestibulo-ocular reflex (for a review see, Leigh & Brandt, 1993), a linear vestibulo-ocular reflex provides stabilization of gaze during translation (Buizza et al., 1980; Smith, 1985; Baloh et al., 1988; Paige, 1989; Paige & Tomko, 1991ab; Israël & Berthoz, 1989; Schwarz, et al., 1989; Schwarz & Miles, 1991). Visually-driven reflexive eye movements (ocular following) that would serve to stabilize gaze during translation have also been described (Miles et al., 1986; Gellman et al., 1990; Busettini et al., 1991). Finally, in addition to these reflexes, voluntary smooth-pursuit eye-movements can also be used to assist fixation of a stationary object during locomotion (for a review, see Keller & Heinen, 1991).

The combination of these four oculomotor pathways would presumably be effective in keeping the image of a stationary point stabilized on the fovea particularly since postural strategies appear to minimize head motion during locomotion, at least to within the working range of the vestibulo-ocular reflex (Grossman et al., 1988; Pozzo et al., 1990) thereby providing an additional tier of control for gaze stabilization. Unless these gaze-stabilization mechanisms are consciously overridden, primates will therefore generally stabilize their gaze during locomotion (Collewijn, 1977; Grossman et al., 1989; Solomon & Cohen, 1992; Leigh & Brandt, 1993). In fact, deficits in gaze stabilization are associated with impaired vision and oscillopsia during locomotion (Takahashi et al., 1988; Grossman & Leigh, 1990).

Gaze stabilization reduces the dimensionality of the self-motion estimation problem by restricting the combinations of translation and rotation that are normally experienced. Our model (Perrone & Stone, 1994) capitalizes on this fact to restrict the original, more general, template model (Perrone, 1992) to a manageable number of templates that can be arranged within 2D cortical maps. **However, the gaze-stabilization assumption (hypothesis 2) should be tested directly by determining whether flow fields that simulate gaze-stabilized self-motion are in fact processed more accurately and precisely than those simulating other forms of combined translation and rotation.**

Roll suppression

Roll body motion (sway) is generally small (less than about 4°/s peak) during human locomotion (Waters et al., 1973; Cappozzo, 1981) and is at least partially compensated for by ocular counterrolling driven by both vestibular and visual inputs (Henn, et al., 1980). Although ocular counterrolling in response to static head tilt has a relatively low gain, recent studies have shown that in the frequency and amplitude range of standard walking (~1 to 3 Hz see, Waters, et al., 1973; Cappozzo, 1981; Grossman, et al., 1988), ocular counterrolling can have gains as high as 0.7 (Vieville & Masse, 1987, Ferman et al., 1987; Peterka, 1992). Finally, head counterrolling may be used to augment the range of ocular roll stability (Gresty & Bronstein, 1992). The above results suggest that oculomotor and postural reflexes will act to minimize roll around the line of sight during normal locomotion. Therefore, we postulated (Perrone & Stone, 1994) that humans do not properly handle roll when processing optic flow. **However, the roll-suppression assumption (hypothesis 3) should be tested directly by determining whether flow fields that simulate no-roll self-motion are in fact processed more accurately and precisely than those that contain roll.**

Theoretical and neurophysiological constraints

Koenderink and van Doorn (1987) showed that performance in heading-from-optic-flow is theoretically limited by the ratio of the rotation rate (in radians/s) to the translation rate (normalized to the average distance of the environmental points, i.e. in units of s^{-1}). On the other hand, Banks and colleagues (Royden et al., 1992, 1994; Banks et al., 1996) have claimed that accurate visual self-motion estimation is limited by an absolute measure of rotation rate (must be less than about 1°/s). We have recently disproved their specific claim by showing that humans are capable of largely accurate heading estimation at rotation rates as high as 16°/s (Stone & Perrone, 1997) but we have only preliminary indication that performance may be linked to the translation-rotation ratio (Fig. 7). Several studies (Maunsell & van Essen, 1983b; Mikami, et al., 1986; Rodman & Albright, 1987; Lagae et al., 1993) have show that most MT neurons (the proposed input units for our detectors) respond best to image motion ranging from ~0.5°/s to ~100°/s (with the median tuned to ~30°/s). From this fact, one would expect human performance to deteriorate outside of this range. **In the proposed study, we wish to examine systematically the relationship between performance and the translation-rotation ratio as well as the absolute flow rate to test the hypothesis that the uncertainty in heading performance will decrease as the ratio increases (hypothesis 4a) and be a U-shaped function of absolute flow (hypothesis 4b).**

Human relative depth estimation from visual motion

It has long been known that observer motion relative to his/her environment can be used to extract depth information (Helmholtz, 1925). Although this relative motion or "motion parallax" has been further explored as a potential source of depth information, pure translation in the fronto-parallel plane (side-to-side) has largely been used as the stimulus (e.g. Rogers & Graham, 1979). Simpson (1988) did measure relative time-to-collision in response to simulated forward translation and combined translation and rotation. Relative time-to-collision is directly related to relative depth in the environment. He found that adding rotation degraded depth estimation. This result suggests that arbitrary rotations cannot be handled but does not resolve whether human depth-from-motion estimation is affected by all rotation or only by specific types of rotational flow. Furthermore, because his environmental stimulus consisted of only two crosses located symmetrically on either side of a fixation cross rather than a full flow field and because subjects received feedback, it is unclear if subjects were truly estimating time-to-collision or merely performing a simple simultaneous 2D speed discrimination task.

Our hypothesis that significant roll flow will interfere with self-motion judgments is however challenged by the finding that roll around the line-of-sight does not appear to degrade visual time-to-impact judgments during simulated pure translation plus roll (Hecht & Kaiser, 1994). However, in their experiments, heading was always along the line of sight which may be a special case. The hypothesis that roll stabilization is necessary for accurate visual heading estimation should therefore be explicitly tested by examining the effect of roll on depth-from-flow judgments when heading is not constrained to lie along the line of sight.

Because our model determines relative depth from the inputs to the most active detector, depth-from-motion estimation is specifically linked to heading estimation. If an incorrect detector responds maximally, both the heading and depth output of the model will be wrong. Conversely if the correct detector wins, the relative responses of the sensor inputs at each location will indeed signal the correct relative depths. **This link between heading and depth estimation from optic flow is a specific prediction of our model (hypothesis 5) that can be tested directly by comparing the sensitivity of human heading and depth estimation to variations in the rotation-translation ratio and absolute flow rate. If our hypothesis is correct, performance in the two tasks will wax and wane together.**

Methods:

Stone and Perrone (1997) in appendix-A4, provides a detailed description of many of the methods to be used as well as a demonstration of the successful application of these methods.

Procedures

Observers will be seated a fixed viewing distance (36 cm) from the display (45° field of view). They will view the screen through a hood that minimizes stray light and eliminates outside visual cues. After a 500 ms fixation period during which they have been instructed to fixate a stationary central cross (1 by 1°), observers will be presented with 400 ms trials of simulated self-motion towards a layout of random dots (~300 points between 12.5m and 25m away[3] with a 6° by 6° blank area over the fixation point[4]). After each trial, they will be asked either to make a two-alternative forced choice or point with a mouse. For the two-alternative forced-choice experiments, the selection of the particular stimulus for a given trial will be done by simple up-down staircasing. For the pointing task, the particular stimulus for a given trial will be chosen randomly from a predetermined set of stimuli (method of constant stimuli). For the head-tilt experiments, the entire set-up (observer, display, and hood) will be mounted on an apparatus that can be tilted along the roll axis (lateral leftward or rightward tilt) at a fixed angle between the observers head and gravity (Fig. 3). Retinocentric heading is the output of ALL current computational models of human heading perception so, to allow direct comparison with model simulations, we measure <u>retinocentric</u> heading (the direction of translation with respect to the line-of-sight) rather than <u>exocentric</u> heading (the direction of translation with respect to the virtual stationary world).

<u>Two-alternative forced-choice heading task.</u> At the end of each trial, observers will be asked to ignore their perceived self-rotation and to respond (left or right mouse click) whether their perceived direction of translation was to the left or right of their line-of-sight (a retinocentric heading judgment). The percent of rightward responses will be plotted as function of heading to yield a psychometric curve. The sigmoidal curves so generated will have y-values that vary from 0 to 100 and will be fit by a cumulative Gaussian using Probit analysis (Finney, 1971). Examples of psychometric curves for a naive observer is shown in Fig. 4. The mean of the best-fitting Gaussian is the point of subjective straight-ahead heading (the value of the heading for which there is a 50-50 chance of responding left/right). The difference between this mean and true straight-ahead is a measure of systematic errors or bias. The bias is a measure of accuracy (no bias meaning perfect accuracy). The standard deviation of the best-fitting Gaussian is a measure of random errors or precision.

<u>Heading pointing task.</u> At the end of each trial, observers will be asked to ignore their perceived self-rotation and to indicate (point and click) with a mouse their perceived direction of translation with respect to their line-of-sight (a retinocentric heading judgment). Headings will range from -15° to +15° in 5° steps (randomly interleaved). Ten repetitions of each heading will be presented with in a each run (~10 minutes). The data from 3-5 runs will be pooled to generate

[3]The absolute values of translation rate and distance, here and elsewhere, are arbitrary. Only the ratio of the two can be recovered from optic flow (i.e. 1 m/s toward a point 10 m away will produce the same flow as 10 m/s toward a point 100 m away). The specific values are provided for clarity: to allow the reader a more concrete sense of the trajectories.

[4] We have found that by blanking the area around the fixation point, fixation is generally well maintained. Under such circumstances, the presence or absence of the fixation cross for the 400 ms of the trial does not produce a significant change in the data (Stone & Perrone, 1997) suggesting that any small eye movements generated do not greatly influednce the results. In a subset of experiments, we will monitor eye movements to assure that fixation was indeed well maintained.

a plot of average perceived heading (±SD) versus true heading which will be fit by linear regression. Veridical perception will yield a line of slope one and intercept zero. Errors can take the form of non-zero intercepts, non-unity slopes, or deviations from linearity. An example of such a curve for a naive observer is shown in Fig. 5A. As a control for pointing motor errors, observers will run in a control condition in which they will be asked to point to a stationary cross presented for 400 ms at various locations (coinciding with the headings presented in the experimental conditions). We have found that observers generate near perfect performance in the control condition indicating little or no motor error (Fig. 5B).

Two-alternative forced-choice relative-depth task. At the end of each trial, observers will be asked to respond (left/right mouse click) whether the red dot(s) were in front or behind the blue dot(s). The percentage of in-front responses will be plotted as function of relative depth to yield a psychometric curve which will again be fit with a cumulative Gaussian. The mean of the best-fitting Gaussian is the point of subjective equal distance (the value of the relative depth for which there is a 50-50 chance of responding in-front or behind). Again, differences between the mean and true equal depth indicates a bias and the standard deviation of the best-fitting Gaussian is a measure of perceptual depth uncertainty.

Stimuli

Visual stimuli will be generated by a SUN SPARC 10 GT on a 20-in SUN multisync monitor (76-Hz frame rate). The software package was developed locally by Philippe Stassart, using the SUN XGL graphics subroutines which take advantage of a dedicated 3D graphics GT hardware accelerator and can therefore simulate sequences of arbitrary motion towards layouts of random dots with arbitrary depth variation in real time. The use of random dots layouts allows for the presentation of optic flow without static perspective or other cognitive depth cues. Because the system is UNIX based and therefore not a real-time system, we were concerned that UNIX-generated interrupts might interfere with stimulus generation so we disabled most interrupts. To test how effective this way, the software has a built-in time checking algorithm that detects missed frames. Using this algorithm, we determined that the system can easily generate optic flow without any missed frames as long number of dots displayed does not exceed ~3000. The spatial resolution of the screen is 1024 by 1024 but the resolution of dot location can effectively be increased by a factor of 8 by hardware implemented anti-aliasing at the expensive of blurring dots over a 3 by 3 pixel grid. Whether or not anti-aliasing is used, the dots do not change size with distance (i.e. no looming cues). For all the experiments, the simulated headings will always be along the horizontal meridian (heading azimuth may vary but elevation will be fixed at 0°) and all simulated rotations will be around a vertical axis through the observers viewpoint (yaw). The presentation duration will be brief (400ms) within the constraints of the finite temporal integration time of human motion processing (Watson & Turano, 1995). With respect to the descriptions below, it should also be emphasized that the simulated trajectories are not directly visible in the stimuli and are merely described to provide a intuitive sense of the stimulus. Observers must recover heading from the optic flow.

Curvilinear motion will be simulated by rotating the observer's line-of-sight at a constant rate around the yaw axis while simultaneously translating the observer in a fixed direction with respect to the current line-of-sight. This is equivalent to generating circular-shaped trajectories with the observer's line of sight fixed at some angle with respect to the tangent of the path (the direction of instantaneous translation). The simulated trajectories will be very short circular arcs. The curvature of the circular path is set by the translation and rotation rates (independent of heading angle). When the rotation rate is 0°/s, curvilinear motion reverts to translation along a straight line (a circle of infinite radius). Heading changes are produced by resetting the line-of-sight with respect to the tangent of the path. When the heading is 0°, observers will experience simulated translation along a circular path as if they were always looking straight-ahead along the tangent of the path (in the direction of their instantaneous translation). When heading is rightward (leftward), observers will move along the same circular path but will now always be looking in a fixed direction leftward (rightward) of the tangent to their path. Throughout every trial, retinocentric heading remains constant, although exocentric heading changes over time as observers experience the simulated turn. Examples of trajectories are shown in Fig. 2 of Stone & Perrone (1997).

<u>Gaze-stabilized translation</u> will be simulated by rotating the observer's line-of-sight at an accelerating rate around the yaw axis while simultaneously translating the observer in a fixed direction with respect to the virtual world. Although the simulated trajectories will be straight lines (pure translation), the resulting optic flow will contain rotational flow from the simulated eye rotation (the rotation is inversely proportional to the simulated fixation distance and accelerates over time). The situation is the converse of that for curvilinear motion. Throughout each trial, exocentric heading remains constant, although retinocentric heading changes over time. Trials will therefore be kept brief (400 ms) and rotation rates low (< ~2°/s) so that retinocentric heading judgments remain meaningful (i.e. retinocentric heading will not change by more than ~1° during the trial).

Observers and Statistics

Each of the experiments will be performed on 6 or more human subjects (the PI and 5 naive observers). The PI has extensive experience that this sample size generally provides adequate statistical power to elucidate significant effects in human visual motion perception (Stone et al., 1990; Stone & Thompson, 1992; Verghese & Stone, 1995, 1996ab; Beutter et al., 1996; Stone & Perrone, 1997; all present data from 6 or fewer observers). If inter- or intra-subject variability should prove higher than anticipated or if effects are smaller than anticipated, then the sample size will be increased appropriately. T-tests (with a $p < 0.05$ criterion) will performed to examine the significance of the effects of head tilt (vs no tilt), added roll (vs no roll), non-stabilized flow (vs stabilized flow) within and across subjects. ANOVAs (with a $p < 0.05$ criterion) will be used to test the significance of trends in the data as a function of rotation-translation ratio, absolute flow rate, tilt angle, and roll rate.

<u>Progress - preliminary and related results:</u>

NASA funding of Dr. Stone over the present funding period (since 1994) has fully or partially supported 9 full-length peer-reviewed publications (See CV for these references: Perrone & Stone, 1994; Stone & Perrone, 1997; Thompson, Stone, & Swash, 1996; Thompson & Stone, 1997, in press; Verghese & Stone, 1995, 1996, 1997; Beutter, Mulligan, & Stone, 1996; Chapman & Stone, 1996), and a NASA technical memorandum (Stone, Beutter, & Lorenceau, 1996). With particular relevance to the study proposed here, we have made progress along two parallel but interactive tracks. We have performed a series of psychophysical studies designed to test the models of human self-motion perception (Stone & Perrone, 1993, 1997). We have also developed and refined a template model of human self-motion perception (Perrone, 1992; Perrone & Stone, 1994). Our major findings are summarized below together with some preliminary results on the effect of varying the rotation-translation ratio and absolute flow rate on heading estimation (Stone & Perrone, 1996).

Heading estimation from optic flow

We have shown that humans make precise and generally accurate estimates of their heading from optic flow even in the presence of rotation. We found that in a simulated curvilinear motion condition, humans could estimate their heading with errors of only a few degrees even in the presence of up to 16°/s of yaw rotation as long as the layout contained points at different depths extending similar results by Rieger and Toet (1985) and Cutting (1986). Fig. 4 shows typical psychometric curves of a naive subject for leftward and rightward 1.5°/s yaw rates. Note that the curves have similar shapes but are shifted with respect to each other. These shifts represent small (-2.7° and +1.6°, respectively) biases in perceived heading in the direction of the rotation. The standard deviations (1.2° and 0.4°, respectively) indicate relatively small perceptual heading uncertainty. This finding is reported in detail in Perrone and Stone (1997).

Physiological validation of the template model

The model's input sensors are by design similar to neurons found in area MT and its output detectors have the emergent property that they respond to 2D flow-field components in a manner similar to neurons within MST (Stone & Perrone, 1994; Perrone & Stone, submitted). The model heading detectors show 'multiple flow component responses' as shown for MST neurons by Duffy & Wurtz (1991a), 'non-immunity to non-preferred flow' as shown for MST neurons by Orban and colleagues (1992), 'spiral tuning' and 'spiral invariance' as shown by Graziano and colleagues (1994), and 'center-of-motion tuning' as shown for MST neurons by Duffy & Wurtz (1995). A systematic evaluation of the model's ability to explain the physiological properties of MST can be found in Appendix-A5.

Ruling out local differential motion models

After performing a series of psychophysical experiments, Warren and Hannon (1988, 1990) concluded that their results ruled out all the current models (at that time) except for "local differential motion models" (Longuet-Higgins & Pradzny, 1980; Rieger & Lawton, 1985; Hildreth, 1992). Longuet-Higgins & Pradzny (1980) pointed out that heading could be recovered during combined translation and rotation by taking advantage of the fact that the translational component of the flow vectors are strongly dependent on point depth while the rotational component is largely independent of depth. They proposed that the visual system takes local differences of two flow vectors associated with points at different depths but in the same position in the visual field because they will have identical rotational components and co-linear (same direction, different speed) translational components. The difference vector will therefore be co-linear with the true translational component independent of the presence of rotational flow. Once the local vector differences are taken, one then returns to the original situation described by Gibson (1950): the FOE of the difference vectors indicates heading. Subsequently, Rieger and Lawton (1985) proposed a more robust version of the "local differential motion" model which allows the use of points which are not immediately adjacent although at the expense of introducing systematic errors. To test this family of models, we designed a stimulus for which there is depth but no local depth differences (Stone & Perrone, 1993). The layout consisted of two half planes at different depths the left and right of the vertical meridian (with a 6° vertical gap centered on the vertical meridian). In this way, there were no adjacent points at different depths. For this "vertical split plane" condition, the Rieger-Lawton model predicts large systematic layout-linked biases towards the farther plane (Fig. 6 - solid symbols). However, this stimulus elicits qualitatively different performance: small motion-linked biases in the direction of rotation (Fig. 6 - open symbols). No local differential motion model can explain this result.

Preliminary psychophysical validation of the template model

We have already shown that the template model can explain human performance in the split-plane condition (see, Fig. 13 of Perrone & Stone, 1994). We have also performed a preliminary measurement of the effect of rotation-translation ratio (Fig. 7) and found as predicted that, within the very limited range tested, performance improves as the ratio decreases (both accuracy and precision are both increases). Finally, we have made a preliminary assessment of the effect of absolute flow rate and found that for forward speeds ranging from 2 to 16 m/s towards two planes of points at 12.5 m and 25 m, that there is little change in the precision of heading judgments (Fig. 8). This results needs to be extended to both lower and higher absolute speeds. Clearly, the psychophysical validation is incomplete because it does not fully test many of the hypotheses of the model: 1) that performance for a fixed layout (i.e. point distances) will be a hyperbolic function of the ratio of the rotation to translation and a U-shaped function of absolute flow rate, 2) that gaze-stabilized (simulated eye) rotations will be processed more accurately than other forms of rotation, and 3) that roll-induced flow will disrupt heading estimation. Lastly, we must determine if static tilt around the roll axis affects heading judgments along the inter-aural axis (i.e. heading azimuth judgments).

Specific Aims:

All 2AFC data will be plotted as percent rightward response versus simulated heading (a psychometric curve) and will be fit with a cumulative Gaussian to yield a mean (bias, a measure of accuracy) and a standard deviation (uncertainty, a measure of precision). All pointing data will be plotted as perceived heading versus simulated heading and fit with linear regression to yield slope (a measure of accuracy), offset (another measure of accuracy) and r the correlation coefficient (a measure of precision). The mean SD of the perceived heading measurements provides a second measure of precision. See Methods for details.

Specific Aim#1: Test the no-effect-of-tilt assumption (hypothesis 1):

Hypothesis:
Static head tilt around the roll axis will have little or no effect on heading estimation.

Objective:
Measure the effect of static head tilt with respect to gravity on human visual heading estimation.

Experiment #1-1:
We will simulate curvilinear motion at 0.5, 1, and 2 m/s with 2°/s of yaw rotation toward the standard field of random dots (~300 points ranging from 12.5 m to 25 m) and measure heading precision (measure of random errors) and accuracy (measure of systematic errors) using the two-alternative forced choice heading task (see Methods). Measurements will be repeated for various static tilts (0, ±15, ±30°, ±45°). We will compare the biases found without tilt (<~2° bias toward the rotation direction was found in Stone & Perrone, 1997) with that found with tilt and measure any effect of tilt amplitude on the biases. We anticipate that, if tilt causes an effect, it will cause a small bias in the direction opposite that of the tilt. If this bias is a systematic error caused by otolith misinterpretation even at 1G, we expect the bias to increase with increasing tilt and to decrease at fixed tilt with increasing forward speed.

Experiment #1-2:
We will simulate gaze stabilized motion at 0.5, 1, and 2 m/s with a mean of 2°/s of yaw rotation toward the standard field of random dots and measure heading precision and accuracy using the heading pointing task (see Methods). Measurements will be repeated for various amounts of static tilt (0, ±15, and ±30°). Data will consist of plots of perceived versus simulated heading. Any interesting errors will manifest themselves as shifts in the intercepts (from linear regression) of these curves. We will compare the offsets found without tilt to that found with tilt and measure any trend in offset with tilt. We anticipate that, if tilt causes an effect, it will cause a small offset in the direction opposite that of the tilt. If this offset is a systematic error caused by otolith

misinterpretation even at 1-g, we expect the offset to increase with increasing tilt and to decrease at fixed tilt with increasing forward speed.

Specific Aim#2: Test the gaze-stabilization assumption (hypothesis 2):

Hypothesis:
Humans will perform best under simulated gaze-stabilization conditions.

Objective:
Measure the effect of deviations from gaze-stabilized flow on the accuracy and precision of human visual heading estimation.

Experiment #2-1:
We will simulate forward motion at 0.25, 0.5, and 1 m/s with yaw rotation toward the standard field of random dots and measure heading precision and accuracy using the two-alternative forced choice heading task (see Methods). Two different simulation scenarios will be compared. Curvilinear motion with a rotation rate of 2°/s and gaze-stabilization with an average rotation rate of 2°/s. To keep the mean rotation rate at 2°/s in the gaze-stabilization scenario, it will be necessary to covary heading and the simulated depth of the fixation point on a trial-by-trial basis and to omit the 0° heading trials. Errors may manifest themselves both as decreased precision (flatter psychometric curves) and biases (shifted curves). We will compare those found in the curvilinear paradigm with those found in the gaze-stabilization paradigm.

Experiment #2-2:
We will simulate forward motion at 0.25, 0.5, and 1 m/s with yaw rotation toward the standard field of random dots and measure heading precision and accuracy using the heading pointing task (see Methods). Two different simulation scenarios will be compared. Curvilinear motion with a rotation rate of 2°/s and gaze-stabilization with an average rotation rate of 1°/s. To keep the mean rotation rate at 2°/s in the gaze-stabilization scenario, it will be necessary to covary heading and the simulated depth of the fixation point on a trial-by-trial basis and to omit the 0° heading trials. Data will consist of plots of perceived versus simulated heading. Errors may manifest themselves either as decreased precision (higher SD for each point), biases (non-zero intercept), and/or distortions (non-unity slope). We will compare those found in the curvilinear paradigm with those found in the gaze-stabilization paradigm.

Experiment #2-3: control for eye-movements
We will re-run a subset of the above experiments while monitoring the subject's fixation using an Infra-Red eye tracker (ISCAN model RK-426) to verify that eye movements are not contaminating the stimulus. Trials in which gaze position deviates by more than 1° from the cross during the 400-ms stimulus will be excluded from the data analysis. We have considerable experience performing simultaneous oculomotor and psychophysical measurements (e.g. Stone et al., 1996).

Specific Aim#3: Test the roll-suppression assumption (hypothesis 3):

Hypothesis:
Adding roll to the optic flow will cause performance to deteriorate.

Objective:
To measure the effect of roll flow on the accuracy and precision of human visual heading estimation.

Experiment #3-1:
We will simulate curvilinear motion at 2 m/s with 2°/s of yaw rotation toward the standard field of random dots and measure heading precision and accuracy using the two-alternative forced choice heading task (see Methods). Various amounts of roll rotation will be added (0, 1, 2, 4, 8, 16, 32 °/s). Errors will likely manifest themselves as decreased precision (flatter curves). We will compare the uncertainty found without roll (~2° was found in Stone & Perrone, 1997) with that found with roll.

Experiment #3-2:
We will simulate gaze stabilized motion at 2 m/s with a mean of 2°/s of yaw rotation toward the standard field of random dots and measure heading precision and accuracy using the heading pointing task (see Methods). Various amounts of roll rotation will be added (0, 1, 2, 4, 8, 16, 32°/s). Errors will likely manifest themselves as increased standard deviations of the points and increased deviation from linearity (i.e. lower r^2). We will compare the uncertainty found without roll (mean SD over headings) and the r^2 of the linear fit with that found with roll.

Specific Aim#4: Determine the self-motion parameters limiting heading-from-flow estimation:

Hypothesis:
Performance is a hyperbolic function of the rotation-translation ratio (hypothesis 4a) and a U-shaped function of absolute flow rate (hypothesis 4b).

Objective:
Measure the effects of the translation-rotation ratio and the absolute flow rate on the accuracy and precision of human visual heading estimation.

Experiment #4-1:
We will simulate curvilinear motion with yaw rotation toward the standard field of random dots and measure heading precision and accuracy using the two-alternative forced choice heading task (see Methods). Various combinations of forward speed (0.25, 0.5, 1, 2, 4, 8 , 16, 32 m/s) and rotation rate will be tested (0.25, 0.5, 1, 2, 4, 8, 16, 32 °/s) so as to produce translation-rotation ratios that vary from 0.125 to 8 (measured in m/° for convenience given the fixed depth range) as well as a wide range of absolute flow rates at fixed ratios of 0.5, 1, and 2 m/°. Errors will likely manifest themselves as decreased precision (flatter curves) and increased biases (shifted curves). We will examine trends in the uncertainty and biases as a function of the translation-rotation ratio and as a function of the absolute flow rate (at fixed ratios of 0.25, 0.5, 1, 2, and 4 m/°).

Experiment #4-2:
We will simulate gaze-stabilized motion with yaw rotation toward the standard field of random dots and measure heading precision and accuracy using the heading pointing task (see Methods). Various combinations of forward speed (0.25, 0.5, 1, 2, 4, 8 , 16, 32 m/s) and rotation rate will be tested (0.25, 0.5, 1, 2, 4, 8, 16, 32°/s) so as to produce translation-rotation ratios that vary from 0.125 to 8 m/° as well as a wide range of absolute flow rates at fixed ratios of 0.5, 1, and 2 m/°. Errors may manifest themselves either as decreased precision (increased mean SD), biases (non-zero offset from linear regression), and/or deviations from linearity (changes in r^2). We will examine trends in these three measures as a function of the translation-rotation and as a function of the absolute flow rate (at fixed ratios of 0.25, 0.5, 1, 2, and 4 m/°).

Specific Aim#5: Determine the self-motion parameters limiting depth-from-flow estimation:

Hypothesis:
Depth and heading estimation are linked such that they will be similar hyperbolic functions of the rotation-translation ratio (hypothesis 5a) and U-shaped functions of absolute flow rate (hypothesis 5b).

Objective:
Measure the effects of the translation-rotation ratio and the absolute flow rate on the accuracy and precision of human depth-from-flow estimation under the same conditions described in Specific Aim #4.

Experiment #5-1:
We will simulate curvilinear motion with yaw rotation toward the standard field of random dots and measure the precision and accuracy of relative depth estimation using the two-alternative forced choice depth task (see Methods). Various combinations of forward speed (0.25, 0.5, 1, 2, 4, 8 , 16, 32 m/s) and rotation rate will be tested (0.25, 0.5, 1, 2, 4, 8, 16, 32 °/s) so as to produce translation-rotation ratios that vary from 0.125 to 8 m/° as well as a wide range of absolute flow rates at fixed ratios of 0.5, 1, and 2 m/°. Errors will likely manifest themselves either as decreased precision (flatter curves) and/or increased biases (shifted curves). We will examine trends in uncertainty and bias as a function of the translation-rotation and as a function of the absolute flow rate (at fixed ratios of 0.25, 0.5, 1, 2, and 4 m/°) and compare them with those observed in Experiment #4-1.

Experiment #5-2:
We will simulate gaze-stabilized motion with yaw rotation toward the standard field of random dots and measure the precision and accuracy of relative depth estimation using the two-alternative forced choice depth task (see Methods). Various combinations of forward speed (0.25, 0.5, 1, 2, 4, 8 , 16, 32 m/s) and rotation rate will tested (0.25, 0.5, 1, 2, 4, 8, 16, 32°/s) so as to produce translation-rotation ratios that vary from 0.125 to 8 m/° as well as a wide range of absolute flow rates at fixed ratios of 0.5, 1, and 2 m/°. Errors will likely manifest themselves either as decreased precision (flatter curves) and/or increased biases (shifted curves). We will examine trends in uncertainty and bias as a function of the translation-rotation and as a function of the absolute flow rate (at fixed ratios of 0.25, 0.5, 1, 2, and 4 m/°) and compare them with those observed in Experiment #4-2.

Experimental Plan:
year 1:
specific aims #2 and #3 will be accomplished.

year 2:
specific aims #4 and #5 will be accomplished.

year 3:
specific aim #1 will be accomplished after setting up the display on the roll apparatus.

Significance:
Anticipating human performance errors during aerospace tasks in which human operators either navigate through or interact with cluttered environments, and designing effective display systems and/or training paradigms to minimize such errors will require an a clear understanding of the factors that limit human self-motion and depth estimation. This project proposes to extend our knowledge of the limits of human self-motion and depth estimation by capitalizing on the previous development of a computational model of human performance, itself derived

from prior measures of human performance and primate neurophysiology. The results of this study in turn will ultimately be used to refine and extend the model and to guide future neurophysiological studies, thus completing the cycle of measuring, modeling, validating. The significance of this study is three-fold: 1) it will provide a clear baseline data set as well as the validation of new sensitive and reliable methodologies necessary for proposing a focused and feasible flight experiment with a high likelihood of success, 2) it will directly test a prominent model of human performance in self-motion perception, thereby aiding in the refinement of a design tool with useful applications towards the efficient and effective development of training paradigms and display technologies, and 3) it will be of interest to the general neuroscience community and will likely help guide future basic psychophysical and neurophysiological research on self-motion processing within the primate extrastriate cortex with potential medical benefits including the development of sensitive diagnostic tools for detecting and quantifying perceptual deficits caused by neural pathology or aging.

The proposed work will provide three significant deliverables which will assist NASA in supporting human exploration of space: 1) an objective and quantitative set of methodologies for measuring human performance in self-motion estimation that have been validated and refined in ground-based experiments, 2) a baseline database of human performance in self-motion estimation that can be compared to performance during or after spaceflight and used to design more focused spaceflight experiments, and 3) an organized set of conditions which are likely to cause astronauts to make erroneous self-motion or depth judgments. The NRA states that "proposals to conduct ground-based research aimed at developing mature flight experiments...are particularly encouraged. (p. 6)" We indeed plan near the completion of this study to submit a proposal to use the same methodologies described herein to quantify spaceflight effects on heading and depth judgments after and possibly during spaceflight. Ultimately, the knowledge gained from the proposed approach could be used to design enhanced training procedures (e.g. Harm et al., 1993) and/or display systems as countermeasures for the potentially dangerous adverse effects of spaceflight on human self-motion and depth perception.

Benefits for Space Exploration. This proposal addresses element emphases in both behavior & performance and space physiology & countermeasures of NRA 96-HEDS-04. Its primary goal is to validate "methodologies to quantify task errors" as requested by the behavior & performance element on p. 24 of the NRA. The proposed technology will clearly benefit any future flight experiment that wishes to examine the effects of spaceflight on self-motion perception. In the space physiology & countermeasures section, the problem of spaceflight-induced "spatial disorientation" and "postural instability" are identified (p. 15) with "identify(ing) mechanisms of changes in sensorimotor and spatial orientation systems...after flight (p. 16)" the first element emphasis. Previous studies have found spaceflight induced alterations in perception and motor control related to self-motion (Parker et al., 1985; Reschke & Parker, 1987; Arrott and Young, 1986; Benson et al., 1986; Arrott et al., 1990; Young et al., 1993; Harm & Parker, 1993; Merfeld et al., 1994). However, the results have been quite variable so firm conclusions have not been possible, potentially for a number of reasons: 1) because vestibular threshold (detection) studies are notoriously difficult to perform as small artifacts (e.g. vibration, noise, proprioceptive or cutaneous inputs) can seriously corrupt the results, 2) because quantitative and objective two-alternative forced choice psychophysical methodologies have not been brought to bear on the potential perceptual reinterpretation of otolith inputs after spaceflight, and 3) because closed-loop motor tasks (e.g. motion nulling) are insensitive to even dramatic changes in sensory processing (negative feedback control loops are designed to do just that). Future flight experiments would benefit from the reliable, objective, and sensitive methodologies that we propose to validate, and from the solid database of normal human performance that we propose to establish.

The proposed work also supports NASA ongoing efforts in enhancing space human factors to support human exploration of space. The first three goals enunciated in the NASA Space Human Factors Engineering Program Plan (1995) present the need 1) to "expand knowledge of human psychological and physical capabilities and limitations in space" by performing research that will "address the ... perceptual... effects of various space mission environments" and developing "quantitative models of human system interactions and capabilities", 2) to "develop cost-effective technologies", and 3) to "increase ... crew safety." The Program Plan furthermore lists as focus areas for research 1) "identifying and defining functions that are critical to safety", 2) "determining ... responses to space" including perceptual, and 3) "identifying critical factors affecting those responses and understanding underlying mechanisms involved in behavior and performance." The Space Human Factors: Critical Research and Technology Definition (1996) lists "fundamental data on human perceptual capacities that are relevant to space missions, including ... motion perception and perception of three-dimensional space" as a critical research need. The proposed work is clearly consistent with the above goals and philosophy as well as NASA's research needs. We propose to acquire fundamental knowledge about human perceptual capabilities in self-motion estimation as a necessary first step in any future study of spaceflight impacts on self-motion estimation and as a specific test of a quantitative model of human performance in self-motion estimation.

Benefits for Aeronautics. Human error is a contributing factor in the majority of aeronautic accidents. More specifically, military pilots have commonly reported that visual-vestibular disorientation has caused critical incidents, defined as experiences "which might lead to some difficulty in flight" (Clark, 1971). Such disorientation has also been the cause of catastrophic accidents (Cohen, 1992), even in recent civilian large-scale aircraft (NTSB aircraft accident report 95/03, 1995). In addition, the increased reliance on enhanced display systems (e.g. head-up displays) has generated new safety issues (e.g. Fischer et al., 1980). Furthermore, in flight simulators (and other virtual environments), the attempt to use visual motion inputs to simulate self-motion can lead to motion sickness (e.g. Kennedy et al., 1989; Hettinger et al., 1990) similar to that of astronauts who face microgravity-induced alteration of visual-vestibular interactions (e.g. Matsnev et al., 1983; Oman et al., 1986). The proposed work will support NASA's efforts in aeronautic R&D by providing engineers: 1) with a tool (the model) that will allow the design of more efficient and effective simulator or cockpit display systems that take advantage of the strengths and minimize the weaknesses of the human perceptual system, 2) with an enhanced knowledge database of visual contributions to self-motion that can be used in the design of enhanced flight simulators with a potential for reducing simulator sickness, 3) with a validated new self-motion estimation algorithm that can be explored as a method for autonomous navigation, and 4) with a methodology that can be used to screen efficiently and quantitatively candidate display designs for how well they convey self-motion information.

Earth-based benefits. After cortical injuries (e.g. car accidents or stroke) or during the natural process of aging, humans can develop deficits in visual function (e.g. Vaina et al., 1990; Shirabe, 1991; Paige, 1992; Spear, 1993). These deficits can have adverse affects on a person's ability to maintain balance or to navigate in his/her environment (Duncan et al., 1993; Patla et al., 1992). However, the subtlest deficits are not always detectable using standard neurological testing. The proposed work will provide a set of tasks that could form the basis of future tests designed to diagnose and evaluate subtle deficits in cortical function as well as provide a clear baseline of normal human performance for comparison with that of patients. Such diagnostic applications need not be limited to clinical situations as, for example, a simple method of screening drivers for visual deficits in self-motion estimation would be more useful than the acuity test now in standard use (Shinar & Schieber, 1991).

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MANAGEMENT APPROACH

Dr. Stone will oversee all aspects of this project. He will bear ultimate responsibility for the experimental design and analysis, and the successful completion of the proposed work. He will devote 35% of his time to this project.

Dr. Cohen will participate in the tilt experiment, totaling 10% time for setting-up and ultimately helping to run the experiments. The TAHRD is in his laboratory at ARC (N239, rm 218) and he will oversee and assure the proper functioning of this device.

The postdoctoral research associate will devote 100% time to this study and will be responsible for the data collection / analysis and manuscript preparation under Dr. Stone's supervision and guidance.

Mr Stassart will perform all of the programming under Dr. Stone's direction.

Mr. Lau will make sure the computer operating systems, hardware, and network are properly maintained and kept up to date. His time is collectively managed by the Vision Group, an informal association of 6 PIs.

PERSONNEL

Dr. Stone has 20 years of experience in scientific research including 10 years devoted to the study of human visual psychophysics and 15 years of experience in oculomotor physiology and behavior. Since obtaining a permanent research scientist position at ARC in 1990, he has set up a state-of-the-art human psychophysics and oculomotor research laboratory. During the current funding cycle (since 1995), he has authored or co-authored 7 full-length publications in high-quality peer-reviewed journals. His CV is in the Appendix.

Dr. Cohen has been at Ames Research Center since 1982, where he served as the Assistant Chief of the Biomedical Research Division, the Chief of the Neurosciences Branch, and as a Principal Investigator and Research Scientist. He is a Fellow of the Aerospace Medical Association, and the recipient of its Environmental Science Award and its Raymond F. Longacre Award for outstanding accomplishment in the Psychological aspects of Aerospace Medicine. He received a Leadership and Service Award from the American Institute of Aeronautics and Astronautics, and is a Senior member of the AIAA. His work on the Lunar and Mars Exploration Initiative Team was recognized by NASA with a Group Achievement Award, and he is also a recipient of the NASA Medal for Exceptional Scientific Achievement. Dr. Cohen is a Fellow and a Past-President of the Aerospace Human Factors Association. His other professional affiliations include membership in the American Association for the Advancement of Science, the New York Academy of Sciences, the Psychonomic Society, and the Society of the Sigma Xi. The theme of his research has largely been concerned with human perception and motor performance, particularly as they are altered by exposure to the unusual environmental conditions encountered in aircraft and spacecraft. Dr. Cohen has presented and published more than one hundred papers in the general areas of human aviation Physiology and Psychology. His CV is in the appendix.

Once the availability of funds is established, a postdoctoral research associate will be recruited. The close proximity of UC Berkeley, UC San Francisco, UC Davis, and Stanford, as well as the PI's close ties to UCB and UCSF (see CV) makes it likely that a high quality fresh-out Ph.D. can quickly be found. Dr. Stone's has already served as an postdoctoral advisor for Dr. Verghese (who is presently working at Smith-Kettlewell Institute for Visual Science) and Dr. Beutter who is currently working on another project at ARC. Both have successfully published their work in Dr. Stone's lab in high-quality peer-reviewed journals (Verghese & Stone, 1995, 1996ab; Beutter et al., 1996; see Dr. Stone's CV for these references).

FACILITIES AND EQUIPMENT

Dr. Stone's laboratory at ARC (building 262, room 217E) is fully equipped to perform all aspects of the visual heading and depth perception experiments. A SPARC 10 (with 64MByte RAM and GT graphics accelerator) will be used for visual display (stimulus generation), experiment management (staircasing), and data acquisition (keystroke or mouse response) for the psychophysical experiments. An specially-modified ISCAN RK-426s and a 486-based PC system are available for non-invasive, binocular eyetracking with up to 240Hz sampling rate capability. Two SPARC LX workstations and an SGI Indigo2 are available for data analysis, image generation, software development, and model simulations. All of the above computers have 1.2GByte Hard drives for data storage and an Exabyte 8500 is used to back up all systems on a weekly basis. Three MacIntosh PowerPCs (8100/80), a Quadras 900, and an LC are available for data analysis and visualization, figure generation, and manuscript preparation. Standard commercially available software packages are available including Mathematica, Igor, Canvas, Excel, MacDrawPro, Cricket Graph, Delta Graph, Word, WriteNow, ThinkC, and Labview. Shared printing (color and B/W laser printers), photocopying, and image processing (VCR, optical disk writer, scanner, image processing software) resources are available in adjoining common Vision Group laboratory (rm 217) as well as a full time System Manager (Mr. Chun Lau) who maintains the network of about twenty computers including those described above and the SGI ONYX which is shared by the group. Secretarial assistance is available though the Human Systems and Technologies Branch office. Library facilities (wide variety of Life Science Journals and database search capabilities) are also available at ARC.

Dr. Cohen's laboratory at Ames Research Center (building 239, room 218) is comprised of six behavioral/perceptual testing rooms covering approximately 1250 square feet. These rooms contain an electrostatically and electromagnetically shielded test chamber, a sound insulated testing room, and three research dark rooms. The laboratory also houses specialized behavioral and perceptual research equipment, including two ISCAN infrared video eye tracking systems, several IBM-compatible pentium-class computers for data processing, several Apple PowerPC computers, a Two Axis Human Rotation Device (TAHRD), a motorized Circolectric bed, several electroluminescent displays, a vertically rotating chair, and other devices needed to perform experimental studies in support of this effort.

PROPOSED COSTS

The majority of the proposed costs are salaries for a full-time research associate (postdoctoral level), 25% of a senior programmer, and 10% of a system administrator. No PI salary or major equipment purchases are requested.

Full-time (100%) support for a research associate is requested as he/she will serve the lead role in the running of visual psychophysical experiments.

Quarter-time (25%) support for Mr. Stassart, the systems programmer, is requested to continue software development and maintenance. His continued participation is critical to the successful completion of this project as he is completely responsible for visual stimulus generation, psychophysical data acquisition and analysis, and real-time synchronization of eye-tracker data acquisition with the visual stimuli. He is a senior graphics programmer with extensive experience in real-time image display and data gathering on both UNIX (the SUN GT display) and DOS (the eye tracker) platforms. This level of expertise is critical to allow real-time control and interaction between multiple systems with the precision necessary for scientific experimentation.

One-tenth time (10%) support for Mr. Lau, the Vision Group system administrator, is requested to provide the PI's share of a joint commitment to support of a large network of SUN and SGI computers. This resource is an extremely efficient and cost-effective mechanism to increase the productivity of many PIs.

NASA only allows Sterling Software Inc. the right to provide research programming support at ARC and the overhead charges have been negotiated with the government. All NASA ARC PIs must abide by the government contractor hiring regulations and overhead costs. The salary for

Mr. Stassart and Mr. Lau's salaries are approximate (unknown to the PI) and their fringe benefits includes the government mandated overhead.

Travel funds for the postdoctoral research associate to present our psychophysical results at ARVO ($400 RT San Francisco - Ft Lauderdale plus $665 per diem for 7 days + $50 for ground transportation) and Neuroscience ($400 RT NewOrleans + $728 per diem for 7 days + $50 ground transportation) are requested. Dr. Stone's travel is covered by US government travel funds and cannot be requested in this grant.

Addition costs include the service contracts ($3750-$4250/year) on the SUN SPARC10 GT computer (stimuli generation and data acquisition), subject time ($8.66/hr x 10 subjects/year x 2hr/run x 4 runs/session x 3 sessions/experiment ~ $2078 except in year 3 in which only 5 subjects will be run), publication costs (page and reprint charges for 2 papers x $500/paper). R&D Program costs are a mandatory ARC overhead charge which is calculated as $10K x (# of civil servant and contractor FTEs = 0.80).

Miscellaneous supplies include software upgrades for 2 Macs, computer and art supplies, and other small expenses (totaling $2000/year).

5% increases in salary and in the service contracts expenses were used for the calculations of the second and third years.

PREVIOUS AND CURRENT SUPPORT

The PI is not funded for the current fiscal year (FY97). In the prior two fiscal years, the PI was supported by NASA seed money. The budget for FY95 was $100K and for FY96 was $60K.

HUMAN RESEARCH

All human research associated with this proposal will be conducted in accordance with the Declaration of Helsinki (Code of Ethics for the World Medical Association) and applicable NASA guidelines for human research (AMMI 7170-1). A human use protocol (HR II - 97-16) was submitted and approved on 3/21/97. The final approval by HRB is included in Appendix A-3.

FIGURES

FORM US-4

CERTIFICATION REGARDING DRUG-FREE WORKPLACE REQUIREMENTS

This certification is required by the regulations implementing the Drug-Free Workplace Act of 1988, 34 CFR Part 85, Subpart F. The regulations, published in the January 31, 1989 Federal Register, require certification by grantees, prior to award, that they will maintain a drug-free workplace. The certification set out below is a material representation of fact upon which reliance will be placed when the agency determines to award the grant. False certification or violation of the certification shall be grounds for suspension of payments, suspension or termination of grants, or government-wide suspension or debarment (see 34 CFR Part 85, Sections 85.615 and 85.620).

I. GRANTEES OTHER THAN INDIVIDUALS

A. The grantee certifies that it will provide a drug-free workplace by:

(a) Publishing a statement notifying employees that the unlawful manufacture, distribution, dispensing, possession or use of a controlled substance is prohibited in the grantee's workplace and specifying the actions that will be taken against employees for violation of such prohibition;

(b) Establishing a drug-free awareness program to inform employees about --
 (1) The dangers of drug abuse in the workplace;
 (2) The grantees policy of maintaining a drug-free workplace;
 (3) Any available drug counseling, rehabilitation, and employee assistance programs; and
 (4) The penalties that may be imposed upon employees for drug abuse violations occurring in the workplace;

(c) Making it a requirement that each employee to be engaged in the performance of the grant be given a copy of the statement required by paragraph (a);

(d) Notifying the employee in the statement required by paragraph (a) that, as a condition of employment under the grant, the employee will:
 (1) Abide by the terms of the statement; and
 (2) Notify the employer of any criminal drug statute conviction for a violation occurring in the workplace no later than five days after such conviction;

(e) Notifying the agency within ten days after receiving notice under subparagraph (d) (2) from an employee or otherwise receiving actual notice of such conviction;

(f) Taking one of the following actions, within 30 days of receiving notice under subparagraph (d) (2), with respect to any employee who is so convicted --
 (1) Taking appropriate personnel action against such an employee, up to and including termination; or
 (2) Requiring such employee to participate satisfactorily in a drug abuse assistance or rehabilitation program approved for such purposes by a Federal, State, or Local health, Law enforcement, or other appropriate agency;

(g) Making a good faith effort to continue to maintain a drug-free workplace through implementation of paragraphs (a), (b), (c), (d), (e), and (f).

B. The grantee shall insert in the space provided below the site(s) for the performance or work done in connection with the specific grant:

Place of Performance (Street address, city, county, state, zip code)

Human Perfroamnce Research Lab
NASA Ames Research Center
Moffett Field, CA 94035-1000

Check ____ if there are workplaces on file that are not identified here.

II. GRANTEES WHO ARE INDIVIDUALS

The grantee certifies that, as a condition of the grant, he or she will not engage in the unlawful manufacture, distribution, dispensing, possession or use of a controlled substance in conducting any activity with the grant.

NASA Ames Research Center, Code AF____________ NASA SOL-NRA 96-HEDS-04
Organization Name AO or NRA Number and Title

Victor Lebacqz, Division Chief, Acting____________
Printed Name and Title of Authorized Representative

____
Signature Date

Leland S. Stone ____________ Human self-motion and depth estimation from optci flow in 1G
Printed Principal Investigator Name Proposal Title

FORM US-5

CERTIFICATION REGARDING
DEBARMENT, SUSPENSION, AND OTHER RESPONSIBILITY MATTERS
PRIMARY COVERED TRANSACTIONS

This certification is required by the regulations implementing Executive Order 12549, Debarment and Suspension, 34 CFR Part 85, Section 85.510, Participants' responsibilities. The regulations were published as Part VII of the May 28, 1988 Federal Register (pages 19160-19211). Copies of the regulations may be obtained by contacting the U.S. Department of Education, Grants and Contracts Service, 400 Maryland Avenue, S.W. (Room 3633 GSA Regional Office Building No. 3), Washington, D.C. 20202-4725, telephone (202) 732-2505.

A. The applicant certifies that it and its principals:

(a) Are not presently debarred, suspended, proposed for debarment, declared ineligible, or voluntarily excluded from covered transactions by any Federal department or agency;

(b) Have not within a three-year period preceding this application been convicted or had a civil judgement rendered against them for commission of fraud or a criminal offense in connection with obtaining, attempting to obtain, or performing a public (Federal, State, or Local) transaction or contract under a public transaction; violation of Federal or State antitrust statutes or commission of embezzlement, theft, forgery, bribery, falsification or destruction of records, making false statements, or receiving stolen property;

(c) Are not presently indicted for or otherwise criminally or civilly charged by a government entity (Federal, State, or Local) with commission of any of the offenses enumerated in paragraph A.(b) of this certification; and

(d) Have not within a three-year period preceding this application / proposal had one or more public transactions (Federal, State, or Local) terminated for cause or default; and

B. Where the applicant is unable to certify to any of the statements in this certification, he or she shall attach an explanation to this application.

C. Certification Regarding Debarment, Suspension, Ineligibility and Voluntary Exclusion - Lowered Tier Covered Transactions (Subgrants or Subcontracts)

(a) The prospective lower tier participant certifies, by submission of this proposal, that neither it nor its principles is presently debarred, suspended, proposed for debarment, declared ineligible, or voluntarily excluded from participation in this transaction by any federal department of agency.

(b) Where the prospective lower tier participant is unable to certify to any of the statements in this certification, such prospective participant shall attach an explanation to this proposal.

NASA Ames Research Center, Code AF__________NASA SOL-NRA 96-HEDS-04
Organization Name AO or NRA Number and Title

Victor Lebacqz, Division Chief, Acting ___________________________________
Printed Name and Title of Authorized Representative

____
Signature Date

:Leland S. Stone______Human self-motion and depth estimation from optic flow in 1G
Printed Principal Investigator Name Proposal Title

FORM US-6

CERTIFICATION REGARDING LOBBYING

As required by S 1352 Title 31 of the U.S. Code for persons entering into a grant or cooperative agreement over $100,000, the applicant certifies that:

(a) No Federal appropriated funds have been paid or will be paid by or on behalf of the undersigned, to any person for influencing or attempting to influence an officer or employee of any agency, a Member of Congress, in connection with making of any Federal grant, the entering into of any cooperative, and the extension, continuation, renewal, amendment, or modification of any Federal grant or cooperative agreement;

(b) If any funds other than Federal appropriated funds have been paid or will be paid to any person for influencing or attempting an officer or employee of any agency, Member of Congress, an or an employee of a Member of Congress in connection with this Federal grant or cooperative agreement, the undersigned shall complete Standard Form - LLL, "Disclosure Form to Report Lobbying," in accordance with its instructions.

(c) The undersigned shall require that the language of this certification be included in the award documents for all subawards at all tiers (including subgrants, contracts under grants and cooperative agreements, and subcontracts), and that all subrecipients shall certify and disclose accordingly.

This certification is a material representation of fact upon which reliance was placed when this transaction was made or entered into. Submission of this certification is a prerequisite for making or entering into this transaction imposed by S1352, title 31, U.S. Code. Any person who fails to file the required certification shall be subject to a civil penalty of not less than $10,000 and not more than $100,000 for each such failure.

NASA Ames Research Center, Code AF NASA SOL-NRA 96-HEDS-04
Organization Name AO or NRA Number and title

Victor Lebacqz, Division Chief, Acting
Printed Name and Title of Authorized Representative

Signature Date

Leland S. Stone Human self-motion and depth estimation from optic flow in 1G
Printed Principal Investigator Name Proposal Title